NOISE REDUCTION BY USING SERRATED TRAILING EDGES

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ABSTRACT

In the JOULE III project *Investigation of Serrated Trailing Edge Noise (STENO)* the application of serrated trailing edges (TE) to reduce the TE-noise of wind turbine blades is considered. The important TE-noise can only be reduced effectively if the tip region is treated accordingly. Serrations reduce the level of TE noise in 2D-flows significantly, what, however, is not verified for the 3D-flow present in the tip region. In STENO, it will be tried to find guide-lines for the optimal application of serrated trailing edges in the tip region of wind turbine blades by wind tunnel tests, numerical prediction methods and free-field measurements.

1 INTRODUCTION AND FORMER RESULTS

The noise of wind turbines is a major problem for the public acceptance of wind energy. The emitted aeroacoustic noise level strongly depends on the effective flow speed. Therefore, almost all aeroacoustic noise is generated in the tip region of the rotor and means for noise reduction should be applied there. For modern well-designed wind turbines trailing-edge noise is the most important aerodynamic broad band noise source [1].

It is generated by the interaction of the boundary layer turbulence and the trailing edge. Its level strongly depends on the local flow velocity and reaches a maximum when the eddies present in the boundary layer of the flow are crossing the trailing edge perpendicularly. In a theoretical investigation [2] it was shown that serrating of the trailing edge will lead to a reduction of the noise emission. Wind tunnel measurements using 2D-sections of wind turbine blades, as carried out in the framework of the Dutch TWIN programme, showed that serrations reduce the level of TE noise significantly [3,4]. However, strong indications were found that the noise-reducing mechanism may be less effective in case the flow deviates from the flow in the wind tunnel. Strong deviations from the 2D wind tunnel flow will certainly occur in the tip region of rotating blades of wind turbines.

2 AIM OF THE PROJECT

In STENO, it is tried to find out whether the reductions obtained in 2D-experiments can be realised in free-field operation with its 3D-flow as well.

It is another purpose of the STENO project to verify numerical acoustic results with free-field measurements.

Therefore geometries of serrations for which the theory predicts high noise reductions are tested under free-field conditions.

The comparison of the theory and the experiments can then be taken to determine guide-lines for the further developement of the theory as well as for the design of serrations for commerically used wind turbines.

3 APPROACH

The whole investigation is divided into three phases.

1.Wind tunnel measurements to gain data necessary as input for the numerical noise prediction code.

2. Definition of the serration's geometry with the best overall noise reduction by use of the numerical prediction scheme.

3. Free-field experiments using the UNIWEX turbine in order to verify the numerical results or to obtain hints for the adaptation of the code.

In this article stress will be mainly laid on the third phase, since phases 1 and 2 were partly presented in [5] and are presented in [6] in more detail in context with the DRAW-project.

3.1 Wind Tunnel Experiments

The wind tunnel experiments were conducted at NLR in close co-operation with another EU-project (DRAW) [7]. For both projects to a large extent the same measuring equipment and partially the same models were used. The models were built in a modular way with exchangeable tip sections and 24 flush-mounted miniature pressure transducers mounted in a removeable strip. In order to have comparable lift distributions for the blade tips in both the uniform flow of the wind tunnel and the flow on the rotor, a corresponding linear twist correction was applied for the wind tunnel models.

For the simulation code the boundary layer velocity profile and the k-ω spectra of the unsteady pressure fluctuations were needed as input parameters. Furtheron the flow-field around the tip including the tip vortex was needed to decide on the arrangement of the teeth on the rotating blades.

Measurements were performed in two complementary wind tunnels. The LST (Low Speed Tunnel) has a larger cross section (3.0 x 2.25 m^2), a small turbulence intensity and allows for models with a higher aspect ratio.

The KAT (Small Anechoic Tunnel) has only a small cross section (0.4 x 0.5 m^2) but a lower background noise level and provides an anechoic environment.

The measurements were performed with unserrated trailing edge models. Hereby the assumption was made, that serrations do not influence the turbulence and flow around the blade too much. This is a fundamental assumption in Howe's theory, which is the basis of the simulation.

3.2 Simulation and Layout

Interaction of flow with a sharp edged object such as an airfoil trailing edge will produce noise. For a semi-infinite flat-plate trailing edge analytical expressions are available that relate the far-field noise to the wave number-frequency spectrum (k-ω spectrum) of the surface-pressure fluctuations induced by the turbulent velocity fluctuations in the boundary layer [2]. For an airfoil of finite chord and with a serrated trailing edge, a boundary element algorithm was developed [8] which considers a single chord-wise strip of the airfoil and uses periodic boundary conditions in span-wise direction. With the measured boundary layer velocities and the k-ω spectra all input data for the numerical code are known.

Calculations for teeth of different aspect ratios were performed to find out an optimal configuration.

3.3 Free-Field Experiments

Free-field experiments were conducted with the UNIWEX turbine, a two-bladed experimental turbine of 16 m diameter. The tower of the turbine is tiltable, allowing for easy access of the blade tips. During the experiments the turbine is, as in former experiments [9], operated with a hybrid rotor, i.e. one blade is equipped with a serrated tip whereas the other one has an unserrated tip. By this strategy the two tips can be measured simultaneously ensuring practically identical wind and rpm conditions and thus enabling a direct comparison of the tips. For the comparison with wind tunnel experiments, wind speed, rpm and pitch are chosen such that comparable flow speed and lift distribution are obtained. The tips are slid onto the original tips and are fixed with glass fiber reinforced adhesive tape. In order to avoid whistling due to laminar separation bubbles the blades were tripped at 33% chord on both the suction and the pressure side.

The tips have a constant chord length of 196 mm plus 40 mm serration or 20 mm tab resp. and a length of 1100 mm. The airfoil is a FX79-W-151A and the tip planform shape a double ellipse. At the trailing edge they have a flush mounted removeable carbon fiber reinforced plastic (CFRP) strip (see Fig. 1) which on one blade is serrated and on the other blade represents a tab of equal additional

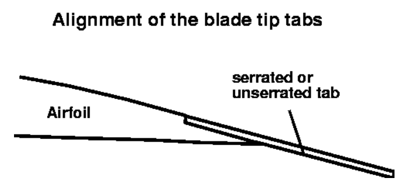

Fig 1. Alignment of the tabs

lifting surface. These strips are continued on the original blade towards the root until they disappear due to the trapecoidal chord distribution of the UNIWEX blades. The tapering-off at the tip is show in Fig. 2. All transitions and steps are thoroughly smoothened to avoid additional noise production.

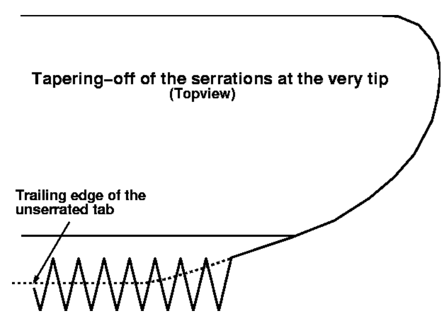

Fig 2. Tapering-off of the tabs at the tip

The acoustic measurements were performed with a parabola of 1.8 m diameter positioned upwind at a distance of hub height plus rotor-radius. The parabola aims for the tip of the down-going blade at horizontal rotor-position thus obtaining the largest distance to the disturbing mechanical/hydraulic noise sources as generator, gearbox and the hydraulic aggregate at the tower foot. The latter one was acoustically capsulated in order to improve the signal to noise ratio of the measurements. A windowing technique is used such that the acoustic signals are evaluated only for the passages of the

blade tips through the sensitive cone of the parabola and such that the blades can be distinguished. The acoustic measurements were evaluated by ECN [10] and supplied both as differences in the sound pressure levels between the serrated and the unserrated tip and as absolute frequency spectra of the two blades respectively (see Fig. 4)
The operational parameters like wind speed and direction, rpm and pitch are monitored by the data acquisition system of the UNIWEX turbine and allow for a correlation with the acoustic data.

4 RESULTS AND DISCUSSION

Since the present article mainly concentrates on the free-field measurements, the results of the first two phases, the wind tunnel tests and the layout of the serrations are only shortly summarised. Besides the needed boundary layer data and the k-ω spectra the wind tunnel experiments showed that the extension of the 3D-flow in the tip region is limited to about half a chord length inboard from the tip [11]. Since due to manufacuring reasons the serrations start only at about one chord length inboard from the tip the orientation for all teeth could be chosen in chord-wise direction. The numerical simulation for the teeth delivered a height-to-base ratio of 2 and a tooth height of 20% of the original chord as an optimum.

Free-field experiments
The *differences* in the sound pressure level (SPL) of the experimental blade and the reference blade are plotted over the incidence angle and over the frequency respectively, and are given in the *surface plot* of Fig. 3. The isolines refer to the difference in the SPL. Positive values indicate that the blade equipped with the serrated trailing edge is more noisy than the reference blade.
Results for frequencies higher than 8 kHz suffer from the fact that their SPL is small - and, therefore, less important - compared to lower frequencies, resulting in poor accuracy for the differences.
Frequencies below 500 Hz are also excluded from the evaluation because they are disturbed by the background noise of the UNIWEX turbine hydraulics. Due to a recently installed acoustic capsulation of the hydraulic power supply of the turbine this boundary frequency could be lowered from 800 Hz to 500 Hz.

From Fig. 3 it can be seen, that for frequencies below 2 kHz there exits a reduction in the SPL of up to 3 dB. For frequencies above 2 kHz an increase was measured with a maximum at 4 kHz. For higher incidence angles this behaviour becomes more pronounced than for small ones.
For very small or even negative angles of attack the noise emission characteristic seems to change its behaviour. For increasing frequency the difference decreases continuously.

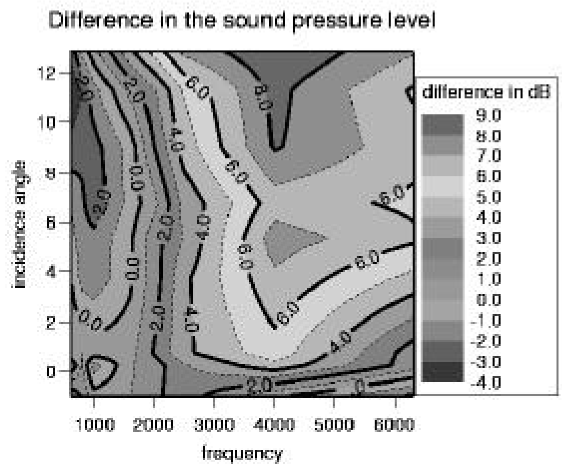

Fig 3. Surface plot of the sound pressure level differences

Analytical results propose, that the decrease in the SPL becomes larger or stays at least constant for increasing frequencies. From such results the measured values deviate more for higher angles of attack than for smaller ones. This could lead to the assumption that phenomena occuring for higher angles of attack are not covered by these analytical methods.
Since the above mentioned surface plot illustrates only the differences in the sound pressure level of the tip with the serrated trailing edge and the reference tip a further representation of the results was chosen.

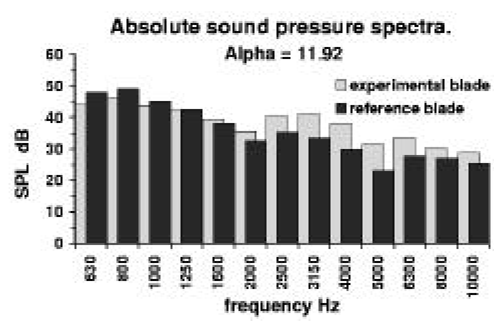

Fig 4. Absolute sound pressure spectra for a geometric incidence angle of 11.92°

Absolute frequency spectra are better apt to demonstrate the effect of serrations on the overall noise performance.
Fig. 4 gives the absolute sound pressure spectra for the serrated and reference tip with respect to a ground board within a frequency range of 630 Hz to 10 kHz and for a

geometric incidence angle of 11.92°.

Although the high frequencies are increased up to 8 dB and the low frequencies are reduced - only- about 2 dB the low frequencies are still dominating the overall acoustic performance of the blade tip equipped with serrated trailing edges for this tested measurement condition.

Therefore the *total sound pressure level* (covering frequencies 630 Hz to 10 kHz), indicates that for incidence angles between 3° and 13° the blade equipped with serrated trailing edges is more silent than the reference blade. In Fig. 5 the difference in the total sound pressure level is plotted over the angle of attack.

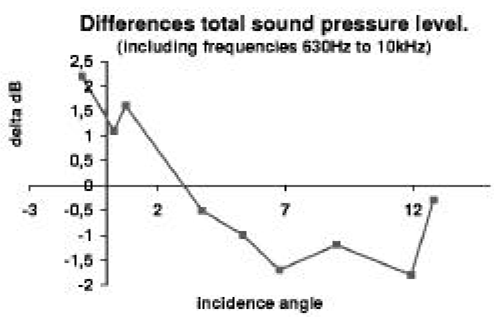

Fig 5. Difference in the total sound pressure level

For low incidence angles the blade with the serrated trailing edge is more noisy than the reference tip. Although higher frequencies are reduced, there can be found no total noise reduction, since a slight increase for low frequencies results in a growth of the total sound pressure level.

For moderate angles of attack the reduction in the low frequency range dominates and leads to an overall reduction of the total sound pressure level of about 2 dB for the case with serrated trailing edges.

For very high incidence angles (>13°) the reduction in the low frequency range starts to vanish again resulting in a decrease of the reduction. The starting turbulent separation at the suction side of the airfoil may be a reasonable explanation.

Summarizing the above results, the tested serrated trailing edge configuration leads to a reduction in the total sound pressure level of about 2 dB for moderate angles of attack.

The reduction is lower than predicted by the theory, which cannot model yet the noise increase for higher frequencies under moderate and high angles of attack.

5 CONCLUSIONS AND OUTLOOK

The wind tunnel experiments showed that the three dimensional flow in the tip region caused by the tip vortex has no major influence on the effectivity of the serration.

In the free-field experiments a reduction in the total emitted noise level of about 2 dB is observed for the range of operational incidence angles (3°...13°) using the described serrations.

However, the reduction is less than theory and numerical calculations predicted and wind tunnel tests revealed. The reasons for that behaviour are not yet completely understood. Further acoustic and flow field investigations in the wind tunnel and free-field experiments will be necessary to find explanations. Nevertheless, some possible explanations and interpretations of the results are given below.

To the present knowledge, among others, the two effects listed below could play a certain role:

- Serrations do influence the behaviour and characteristics of the boundary layer flow in contrast to the assumptions drawn in the basic theory by Howe.

Assuming a pressure jump perpendicular to the serrations the streamlines within the boundary layer get distorted perpendicular towards the teeth edges resulting in less noise reduction efficiency. Furthermore this coincides with an increase in the effective trailing edge length. Since the streamlines of high frequency perturbations are located in flow layers with small convective velocities they are more distorted than low frequency perturbations with higher convective velocities.

- The serrations have been aligned with the suction side surface of the airfoil to avoid flow across the serrations.

For higher angles of attack, however, this may not be optimal. Increasing the pressure jump perpedicular to the teeth, i.e. increasing the incidence angle, results in the above mentioned distortions plus a flow through the serrations. This flow in turn causes additional small scale turbulence due to separation on the teeth’s suction side and therefore, additional high frequency noise.

The distortion of the streamlines will cause mass compensation flow that will also affect the large scale turbulence in upper boundary layers.

In the presence of a pressure jump perpendicular to the teeth’s plane the boundary layer structure is influenced by the serration’s geometry. Increasing the incidence angle mainly perturbations of the pressure side are skewed due to the direction of the pressure jump, resulting in less reduction or even increase in the emitted sound pressure level based on additional small scale turbulence. The low frequency noise dominated by the large scale fluctuations of the suction side is affected by the serrations more or less as predicted by the theory. Since it is the dominating frequency range for the investigated wind turbine the application of serrations led to an overall noise reduction.

Having assumed the pressure jump as one main driving force, its reduction will be the aim of the next free-field measurement campaign with the UNIWEX turbine. The pressure jump mainly occurs due to the resulting blade load and due to the serration's thickness.
Therefore the serrations will be curved in the direction perpendicular to the airfoil surface along the streamlines of the undisturbed airfoil reducing the resulting pressure jump due to the blade load.
Serrations with a higher aspect ratio will be tested in the next measurement campaign, as well.

6 ACKNOWLEDGEMENTS

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